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Abstract: *This paper reviews the experiments on the laser produced electron-positron jets using large laser facilities worldwide. The goal of the experiments was to optimize the parameter of the pair jets for their potential applications in laboratory-astrophysical experiment. Results on tuning the pair jet's energy, number, emittance and magnetic collimation will be presented.*

1. Introduction

Relativistic electron-positron pair plasmas and jets are believed to be abundant in many astrophysical objects and are invoked to explain energetic phenomena related to Gamma Ray Bursts, Active Galactic Nuclei, and Black Holes [1-9]. Making a relativistic electron-positron (antimatter) plasma in the laboratory that is astrophysical-relevant has been challenging due to the difficulties associated with producing high density of the pairs, the short lifetime of positrons, and their highly relativistic energies. As a result, the experimental platforms capable of simulating astrophysical conditions have so far been absent. In the past few years, groundbreaking steps have been made using high-energy ultra-short laser pulses to make large numbers of positrons in a small volume [10]. These laser produced relativistic electron-positron are jet-like and have the natural property of high energy and high density, which is ideally suited to simulate the astrophysical jets. In this paper we review the experimental effort on optimizing the parameter of the pair jets for their potential applications in laboratory-astrophysical experiment using large laser facilities worldwide.

2. Tuning the Parameters of Laser Produced Pairs

Positrons produced from intense laser-target interactions have several characteristics that may prove essential for making it a laboratory-astrophysics relevant relativistic pair plasma. The first is that intense lasers can make a very large number of positrons (10^{10} to 10^{12} per shot) in a short time (1 – 100 ps) [10]. This feature, in combination with the small volume (~mm^3) these positrons occupy, leads to a high density of positrons, even though only for a very short time. The second characteristic is that the target sheath field can accelerate these positrons to 10s of MeV, enabling positrons to be made and accelerated to the relativistic regime in one integrated process. The third characteristic is that MeV electrons and positrons produced from the laser-target interaction form overlapping jets behind the target, allowing much higher pair density to be achieved than it would be if the pairs were distributed isotropically.

In the past few years, extensive experimental work has been carried out by our collaboration. We have performed experiments on the Titan and OMEGA EP lasers in the USA, as well as at the Osaka LFEX in Japan and AWE Orion laser in the UK. These experiments focused on understanding the physics of positron production, beam emittance of the jets, scaling with laser parameters and collimation. The results are summarized below.

2.1 Beam emittance

Emittance is a basic parameter that describes the quality of particle beams and can be derived through measurements of beam divergence and source size. We measured these two parameters for different positron energies under various laser conditions. The divergence angle (full-width at half-maximum) was found to be 20 ± 6 degrees for laser energy of ~300 J at 10 ps (the positrons distribution was peaked at ~12 MeV); ~ 22 degrees for ~850 J, at 10 ps pulse duration, where the peak of the positron energy distribution shifted to ~18 MeV due to the higher laser energy. We found that both the positron beam divergence and source size varied as a function of positron beam energy at the peak of its distribution. The source size varied between 800 and 400 mm for peak energies between 6.5 MeV and 16 MeV, respectivelyThe new results show that the emittance of laser-produced positrons is 100 – 500 mm-mrad, comparable to that obtained at the Stanford Linear Collider [11].

2.2 Scaling

The positron yield as a function of laser energy is not linear [13]. This is surprising, since, assuming that the fraction of absorbed laser energy is constant, one would expect the positron yield to be linearly proportional to the laser energy. Our result indicates that another physics parameter becomes important when the laser energy is higher than about 1 kJ. For example, simulations have shown that the electron reflux factor and the enhancement of the hot electron temperature appear to play a less important role at intensities in the range 10^{18} – 10^{19} W/cm^2, but can no longer be ignored when it is higher than 10^{19} W/cm^2, corresponding to laser energies higher than 1000 J.

2.3 Confinement

The ultimate goal is to confine the particles to make a relativistic charge-neutral electron-positron pair plasma. If successfully confined, the electron-positron plasma would offer a novel system to enable a detailed study of some of the most exotic and energetic systems in the universe. We performed initial experiments on the OMEGA EP laser system (at ~1 kJ over 10 ps), which were designed to collimate the positron jets produced in high intensity laser-plasma interactions. The targets were of 1-mm-thick gold. Previous experiments by this team have shown that quasi-monoenergetic relativistic positron jets with a beam divergence of 30˚ were formed during high-intensity interactions with thick gold targets [10]. The current experiments were designed to collimate the positron jet with an external magnetic lens. Using the recently developed magnetized-inertial fusion electrical delivery system (MIFEDS) [15], strong collimation of both positrons and electrons were observed. This results in a "near-pencil" beam with an equivalent beam divergence angle of 5˚. The charge imbalance was reduced from ~100 (no collimation) to ~ 2.5 (with collimation), a significant step towards making a charge neutral electron-positron pair plasma in the laboratory. A jet of positrons and electrons was emitted from the rear side of the target. Between the target and the detector, MIFEDS coils produced peak magnetic field of about 7 Tesla. The collimated beams were measured with a magnetic electron-positron spectrometer. Without the external magnetic field, the peak densities are about 10^{13} and 10^{15} cm^{-3} for positrons and electrons, respectively [10]. With the external B-field applied, a factor of ~40 increase in the peak positron signal was observed [16].

4. Summary and Future plan

We have shown that the laser-produced positrons have a geometric emittance between 100 - 500 mm-mrad, comparable to the positron sources used at existing accelerators. With 10^{10}-10^{12} positrons per bunch, this low-emittance beam, which is quasi-monoenergetic in the energy range of 5 – 20 MeV, may be useful as an alternative positron source for future accelerators.

Building upon the progress as described in this paper, our next step is to attempt trapping the particles in order to create a pair plasma. This will be a very challenging task as the particle energies are relativistic and the particle flux is orders-of-magnitudes higher than that obtained from conventional sources such as radioactive isotopes. With the development of high power lasers and the pair collimation schemes, we hope to eventually use the multi-kilojoule, short-pulse laser systems worldwide, in combination with more advanced target designs, to create the first relativistic high-density pair plasmas in the laboratory - a completely novel system enabling detailed study of some of the most exotic and energetic systems in the universe [1-9].

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